Leonid Dust Trail Theories

D.J. Asher

Armagh Observatory, College Hill, Armagh BT61 9DG, UK

dja@star.arm.ac.uk

Abstract

At the end of the 19th century, Irish astronomers Johnstone Stoney and A.M.W. Downing showed in principle how to predict meteor storms. Their work and later developments applying similar ideas are reviewed here. The theories essentially involve determining the dynamical behavior of dust trails, which are narrow, dense structures within a broader stream. The formation of dust trails and the main features of their evolution are explained. Some Leonid dust trails are perturbed by the planets so as to result in meteor storms at the start of the 21st century.

1 A hundred years: from Stoney and Downing to the 1999 Leonid storm

1.1 IRAS trails and meteor storms

In 1983 the Infra-Red Astronomical Satellite (IRAS) discovered narrow, dense trails of meteoroids and dust near the orbits of some known short-period comets. It was clear that there are similar trails associated with many periodic comets, those detected by IRAS generally being in cases where the comet was near perihelion during the IRAS mission.

It was recognized that the Earth's passages through such dense trails correspond to the occurrence of meteor storms (see Sykes & Walker 1992, Kresák 1993). As the trails are narrow, it follows that at any given time most trails will not intersect the Earth's orbit in 3-dimensional space. However, the gravity of the planets continuously perturbs the orbits of dust and meteoroid particles in the trails, and from time to time, a trail (or a subsection of a trail) is brought to Earth intersection. A meteor outburst results, provided that the Earth and the particles in that subsection of the trail reach their intersection point at the same time.

Therefore by calculating the gravitational perturbations on sections of trails that might come near the Earth, meteor storms can be predicted. This idea has been considered at various times, albeit not always using the term 'dust trail' to describe the theory involved. Indeed, some of the studies in question date back to before IRAS detected the cometary dust trails.

The orbit of the Leonid parent comet, 55P/Tempel-Tuttle, comes closer than most comet orbits to the Earth's orbit. The total perturbation required to bring Leonid dust trails to Earth intersection is therefore smaller than for trails associated with most other comets, and the Leonid stream provides a primary candidate for meteor storms.

1.2 Stoney and Downing's ortho-Leonids

From the impressive Leonid displays of the 1860s, and others at earlier epochs, it was known that during every cycle of ~ 33 yr, there were at least two or three successive years carrying some possibility (but not certainty) of a Leonid storm. Stoney & Downing (1899a) wrote

> The ortho-Leonids at present form a compact stream of such a length that it takes nearly three years to pass each point of its orbit, and so narrow that when the earth passes obliquely through it the transit occupies only some five or six hours; whereas the clino-Leonids form a less dense and wider stream, which has spread itself the whole way round the ring, and which produces in every November, when the earth passes through it, a feeble meteoric shower that lasts for several days.

The authors use the term 'ortho-Leonids' to refer to what, in the light of the phenomenon observed by IRAS, I am calling a dust trail, and 'clino-Leonids' to refer to the background Leonid stream. Current knowledge of cometary physics makes it clear that new meteoroidal material, capable of forming into a trail, is being released at ~ 33 yr intervals, every time 55P/Tempel-Tuttle returns to perihelion. In addition, the availability of digital computers, to enable fast calculation of the dynamical evolution of the meteoroids, allows us to know now that not just a single compact stream of ortho-Leonids, but rather several separate Leonid trails (each formed at a different perihelion passage), exist simultaneously, and that they can lengthen to take even more than three years to pass a given point (see Section 2.1). Of course, Stoney and Downing recognized that *some* kind of dense, compact structure, which gives rise to storms, exists within the background stream. But more than this, they identified all the essential points about the gravitational perturbations on this 'ortho-stream':

> ... the meteors which occupy successive positions in the procession are differently affected by the surrounding planets ... The dense part of the stream, with which we are chiefly concerned, and which we may call the ortho-stream, is now so long that it takes between two and three years to pass each point in its orbit, so that the configurations in which the several parts are presented to the disturbing planets are markedly different. Accordingly, perturbations must have produced in this long stream both sinuosities and an unequal distribution of density ...

The most important idea is *differential perturbations*. If two points are two or three years apart, their separation in space can increase to several astronomical units, and there may at some time be substantial perturbations from, for example, Saturn, at one point, while the other point is at that time too distant from Saturn for the same effect to occur. As successive sections of a trail are perturbed differently, only a particular section might be perturbed to intersect the Earth's orbit. As regards meteor storms, the relevant question is whether the various sections of each Leonid trail that reach the ecliptic in each mid-November (i.e., short sections of each trail spaced one year apart) intersect the Earth's orbit or whether they miss it (Section 2.2). Stoney and Downing showed how, in principle, exact predictions of meteor storms can be made.

In the above quote they refer to 'sinuosities'. This is a corollary of the differential perturbations: particles at different points along a trail are each perturbed on to slightly different elliptical orbits, and the perturbations can shift trail sections either inside or outside of an

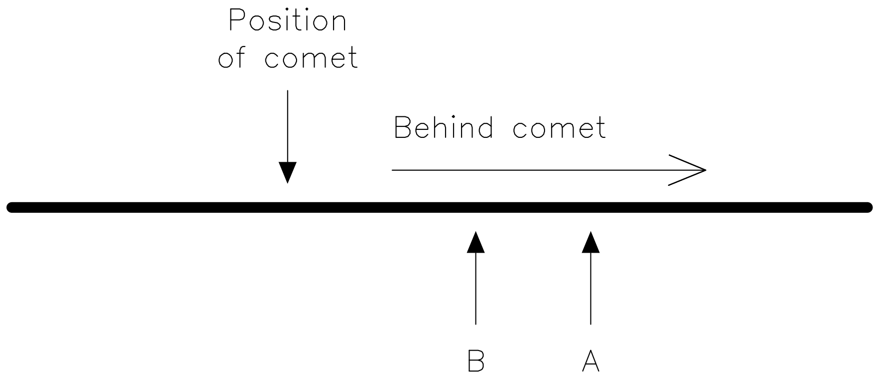

Figure 1: *Schematic diagram of part of a trail, illustrating Stoney and Downing's ideas. The comet was lost in 1899, but is now known to have crossed the ecliptic in 1899 July. The segments of the trail indicated B and A respectively cross the ecliptic in 1899 November and 1900 January. Different segments of a trail undergo different planetary perturbations and so intersect the ecliptic at different points, although if one segment is not too far along the trail from another then the ecliptic crossing points may be close to each other. Since the Earth goes through the Leonid stream in November, it is B that is relevant for determining whether a meteor storm occurs. In fact, all trail segments, that crossed the ecliptic in 1899 November, did so at a large distance from the Earth's orbit (Figure 3), and so no meteor storm occurred.*

idealized 'mean orbit'. Knowing that several trails coexist, the overall dust trail structure can be pictured as multiple, sinuous (or wavy) strands flowing through the Leonid stream as a whole.

Stoney and Downing applied the theory to the eagerly awaited 1899 Leonids, taking as their starting data point the section of the trail (ortho-stream) observed in the great 1866 display, which they termed 'segment A'. They adopted the orbit that Adams (1867) determined, from the 1866 radiant and an orbital period based on the long term cyclicity in Leonid storms. Evaluating perturbations through to the 1899 epoch, they calculated that segment A was shifted more than 100 Earth diameters inside the Earth's orbit, and noted that the ortho-stream would therefore have to be at least that wide for the Earth to encounter it in 1899. Stoney & Downing's (1899b) suggestion, that the ortho-stream probably *was* that wide, was based on a theory (discussed by Stoney 1899) that the Leonids were originally drawn into the solar system by Uranus. We know today that Leonid meteoroids originate during cometary activity around perihelion and that trails are not that wide.

Stoney & Downing (1899a) also calculated the longitude at which segment A would pass through the ecliptic. If there were to be an encounter (i.e., if the ortho-stream were wide enough), the date at which the Earth reached this longitude would give the peak time of the meteor outburst. This calculation of the ecliptic crossing point (cf. Figure 3 below), both its longitude, and its miss distance inside or outside the Earth's orbit, is the same procedure that enabled the prediction of the 1999 Leonid storm (Figure 8 in Section 2.2).

The perturbation calculations showed that segment A would pass through the ecliptic on 1900 January 27, and that strictly, more relevant for 1899 November would be the ecliptic crossing point of a section of the ortho-stream ('segment B') a couple of months ahead of A (Figure 1). The authors noted that their conclusion therefore

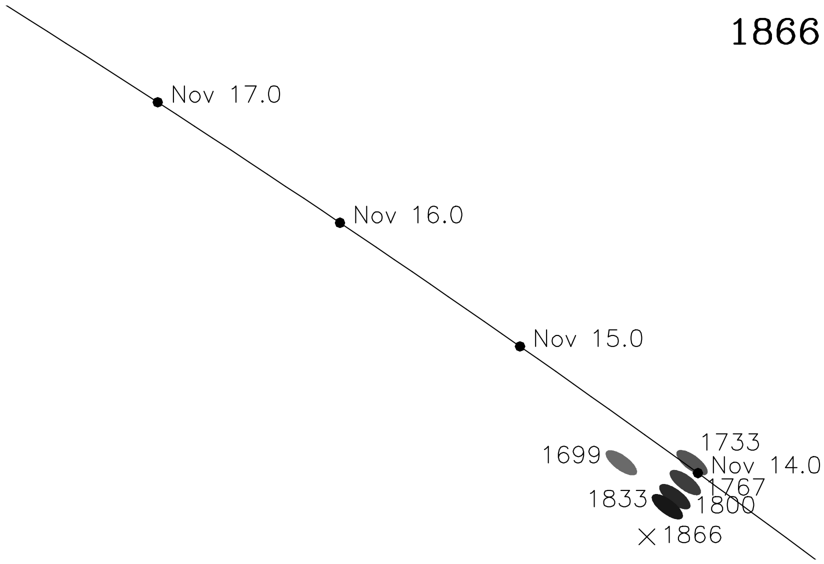

Figure 2: *Cross sections of dust trails that passed through the ecliptic in 1866 November. Each trail is labeled by the year (of perihelion return of 55P/Tempel-Tuttle) when it was generated. Trail cross sections are discussed by McNaught & Asher (1999a, b), but here they are idealized as ellipses. The cross indicates where the comet passed through the ecliptic (at its descending node) in 1866 January, and does not represent a dust trail; although an incipient trail was present in 1866 January (due to material being released at that perihelion passage), it would not have extended far from the comet and so was not there in 1866 November. The Earth's orbit is shown, and the Earth's position, exaggerating its physical size 10 times, at dates (Universal Time) in 1866. If projected on to the ecliptic, Leonid trails would in this region run nearly parallel to the Earth's orbit, with Leonid meteoroids traveling in the opposite direction to the Earth; Leonid orbits are inclined ∼18° out of the ecliptic.*

> ... rests on two assumptions: (1) That segments A and B were, in 1866, moving in orbits that did not much differ; (2) That the perturbations which segments A and B have since suffered have not much differed.

Today we adjust our starting data point (analogously to considering segment B instead of segment A) and quickly run another iteration of a computer program that evaluates perturbations.

> The expense of carrying on the work has been met partly out of the Government Grant administered by the Royal Society, and partly out of the Royal Society's Donation Fund. The computations have been made by Messrs. F. B. Cooper, J. H. Bell, and W. H. Walmsley, members of the staff of the Nautical Almanac office ...

A hundred years ago, one would probably have had to request an extra research grant! The authors therefore drew their conclusions from their segment A calculations, although later (Stoney & Downing 1900) they performed calculations for ortho-Leonid segments a year ahead and a year behind, i.e., relating to the 1898 and 1900 Leonids. But in any case, an extra iteration, i.e., computing segment B to check their assumption (2), could not have solved the problem completely, because the accuracy of the result is limited by the accuracy

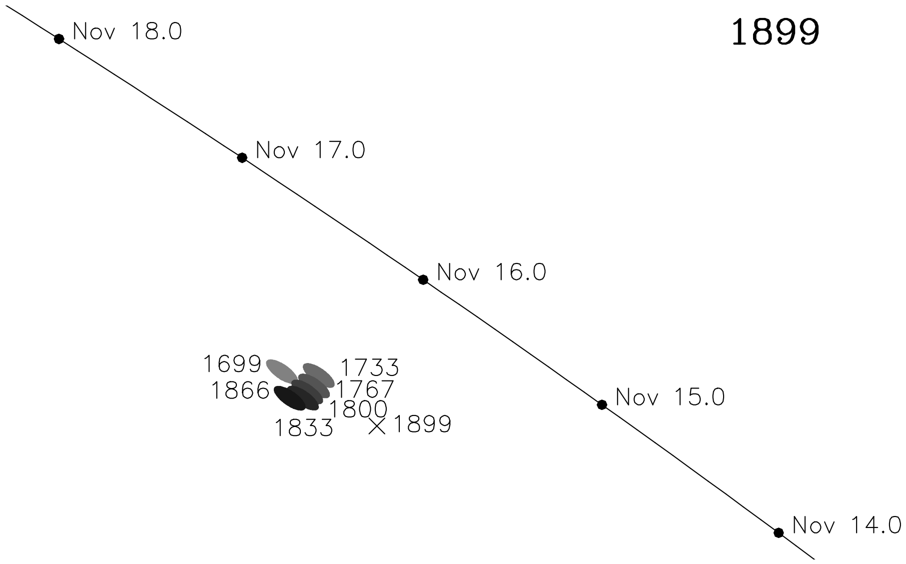

Figure 3: *Cross sections of dust trails that passed through the ecliptic in 1899 November. All these trails except 1866 appear in Figure 2 but the cross sections are at different points along the same trails. The cross indicates where the comet passed through the ecliptic in 1899 July.*

of the starting data — cf. their assumption (1). Stoney and Downing realized the inherent uncertainty in an orbit determined from the 1866 radiant, and a direct determination of an orbit for the unobserved segment B was not, of course, possible. To achieve the highest precision, the essential starting data are the orbital elements of the comet at each of its most recent perihelion times (i.e., not only in 1866, but in 1833, 1800 and a few more), since it releases new meteoroids on each return. However, the known observations of 55P/Tempel-Tuttle at the end of the 19th century covered just seven weeks during the discovery apparition in 1865–66. Although Oppolzer's (1867) orbit was the best fit to those available observations, and indeed allowed the connection between Tempel-Tuttle and the Leonids to be recognized, more recent determinations using observational arcs of centuries rather than weeks show that Oppolzer's orbital period differed by 0.3 yr from the genuine value in 1865–66. This would therefore have limited the accuracy of the findings even if Stoney and Downing had used the comet orbit.

Nevertheless, Stoney & Downing's (1899a) paper can fairly be regarded as a landmark in understanding the cause of meteor storms, demonstrating the effect of planetary perturbations on nodal crossing points. For the purpose of visualizing trail crossing points, it is perhaps of interest to plot trail cross sections in the ecliptic plane. Figures 2 and 3 depict the situations in November 1866 and 1899. Figure 2 shows that the largest contribution to the 1866 storm came from meteoroids in the 1733 trail, which was then 4 revolutions old. The plotted cross section of that trail can be taken as analogous to Stoney and Downing's segment A (since A was based on the 1866 storm), in which case the cross section of the 1733 trail in 1899 November (Figure 3) corresponds to their segment B. The correspondence should not be regarded as exact, since data for these Figures have been calculated by using accurate orbital elements for the comet at 1733 and other epochs, which are available now (e.g., Yeomans *et al.* 1996, Nakano 1997, 1998) but were not in 1899. However, the effect of perturbations calculated by Stoney and Downing for segment A, the shifts in position both inside the Earth's orbit and to greater longitude, are within 10% of the displacement between the 1733 trail cross sections in Figures 2 and 3. This quantitatively validates their assumptions (1) and (2) mentioned above, albeit discrepancies of this size must be removed for high precision storm prediction.

1.3 Recovery of Tempel-Tuttle, and further trail studies

Based on Schubart's (1965) prediction, observers were just in time to recover 55P/Tempel-Tuttle at its 1965 apparition before it disappeared back to the outer solar system for another thirty years. With the resulting greatly increased accuracy in its orbit, significant advances in Leonid storm calculations were possible. Knowledge of the comet orbit (which is perturbed just as particles in dust trails are) at each perihelion return constrains the initial orbits of meteoroids in the trail generated at that return, and so is necessary for predicting meteor storms. Of course, the comet orbit alone is not sufficient, because the perturbations on the comet and on (the relevant sections of) trails are different, i.e., one must evaluate the latter.

Orbits (i.e., sections of trails) have to be identified with an appropriate period that brings them to cross the ecliptic in mid-November. Although identifying these orbits is not completely trivial because perturbations cause the period to change continuously (Section 2.1), they can generally be identified reasonably quickly using an iterative procedure. Evdokimov & Kondrat'eva (1972) found that a suitable orbital difference from the comet in 1800 could lead to an ecliptic crossing very near the Earth in 1833 November (the comet itself crossed the ecliptic in 1833 January), and similarly traced an orbital difference in 1899 through to 1966, although the accuracy achievable at the time meant that these solutions were not proved uniquely. Among the papers noted in Rao's (1999) review of Leonid dust trail work is that of Upton (1977). Upton drew attention to the differing perturbations acting on material released at different perihelion returns (i.e., in separate trails), finding which trails caused the great 1833 and 1966 displays, and correctly predicting the occurrence and cause of the 1999 storm. The accuracy of Evdokimov & Kondrat'eva's study was improved by Kondrat'eva & Reznikov (1985), and the calculations of Asher (1999) and Brown (1999a), the latter based on a full model of the Leonid stream including detailed consideration of the ejection model, also identified the 1800 and 1899 trails as the primary components respectively contributing towards the 1833 and 1966 storms.

Kondrat'eva & Reznikov (1985) also predicted the Earth's encounters with the 1899 trail in 1999, and with the 1866 trail in 2000, 2001 and 2002. Those last three encounters are thus with sections, spaced a year apart, along the same trail. By the time of the 1999 Leonids, Kondrat'eva *et al.* (1997), McNaught & Asher (1999a), and Lyytinen (1999) had each generated a list of those and other encounters. They all evaluated the differential gravitational perturbations on orbits of different period, it being the different period, whether due to ejection velocity or radiation pressure, that causes particles to separate along a trail (Section 2.1). The calculations yield a theoretical ecliptic crossing point, whose longitude and miss distance from the Earth's orbit (cf. Sections 1.2, 2.2) are of interest. Kondrat'eva & Reznikov (1985), McNaught & Asher (1999a) and Lyytinen (1999)'s predictions of the 1999 Leonid peak time all agreed, ranging from Nov 18, $02^{\mathrm{h}}08^{\mathrm{m}}$ to $02^{\mathrm{h}}10^{\mathrm{m}}$ UT, with Upton's (1977) calculated time being 'close to 2 am.'

Other research applied the same principles to other streams capable of producing outbursts. Davies & Turski (1962) considered whether ejections from 19th century perihelion passages of 21P/Giacobini-Zinner could have led to the 20th century storms and outbursts in the

Draconid (Giacobinid) shower. Although later work showed that 20th century ejections (i.e., dust trails generated during 20th century returns of the comet) were relevant for such meteor displays as 1933 and 1946, so that Davies and Turski's paper was not the definitive answer to the Draconid problem, they illustrated how orbits of differing period undergo differential gravitational perturbations. Their work was thus similar to so-called dust trail theories. Further investigations (references in Reznikov 1993) were done by Evdokimov and also by Reznikov into the cause of the 1933 and 1946 Draconid storms, and subsequently Reznikov's (1993) paper was quite an extensive study of the possibilities for Draconid outbursts from 1985 to 2025. Reznikov's perfect calculation in advance of the 1998 Draconid outburst (relating to the dust trail generated at the 1926 return of 21P/Giacobini-Zinner) demonstrated the accuracy of the storm prediction technique.

Similar investigations can be done into other streams. The technique has been applied by Reznikov (references in Kondrat'eva *et al.* 1997) to the Bielids and June Bootids, and by Lyytinen (2000) to the Perseids. Altogether, meteor storm prediction has now become achievable at a high level of precision.

2 Dust trails

2.1 Why dust trails exist; density distribution along trail

When meteoroids escape from a comet, the velocity they have relative to the comet nucleus causes their orbits to differ slightly from the comet's orbit. Although there are differences in all the orbital elements, the important parameter, as regards the formation of a trail, is the orbital period. If a meteoroid's period differs by ΔP_0 from the comet's period P_0, then they gradually separate along the orbit, the amount of time by which the meteoroid lags the comet after n revolutions being

$$\Delta T = n\,\Delta P_0 \tag{1}$$

More often than not, the semi-major axis a is used rather than P, in work on orbit evolution. They are equivalent by Kepler's 3rd law of planetary motion

$$P = a^{3/2} \tag{2}$$

Using (2), (1) becomes

$$\begin{aligned} \Delta T &\approx n\,\frac{3}{2}\,a_0^{1/2}\,\Delta a_0 \\ &= \text{constant} \times n \times \Delta a_0 \end{aligned} \tag{3}$$

Δa_0 can be negative or positive: obviously, meteoroid particles with smaller and larger period than the comet respectively get ahead of and fall behind the comet. Since the particles released during any one perihelion passage will cover a range of values of Δa_0, the result is that the particles must gradually stretch into a trail (Figure 4), with the extent of the range in Δa_0 determining the rate at which the trail lengthens. The quantities ΔT, Δa_0 and n are related by equation (3). If one considers a fixed displacement (in time) behind the comet, e.g. $\Delta T = +1\,\mathrm{yr}$, then the particles at that point are continuously changing, i.e., different

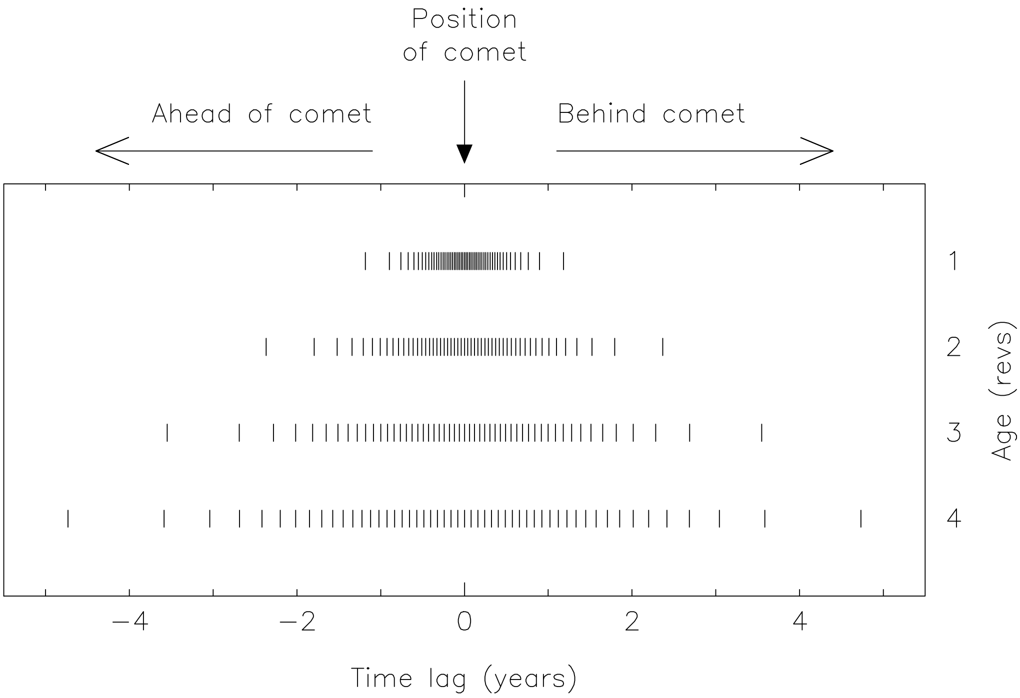

Figure 4: *Evolution of a Leonid dust trail, shown after 1, 2, 3 and 4 revolutions, neglecting radiation pressure and gravitational perturbations. The x-axis is the time by which particles lead or follow the comet. In this representation, particle density in the trail is inversely proportional to spacing between lines. Two points to note are:*

(i) At any one time, the density profile along the trail shows a concentration close to the comet. The extent of this concentration could be adjusted (compressed or expanded) depending on the assumed model of ejection from the comet nucleus (in general, smaller ejection velocities give a smaller range of meteoroids' orbital periods, and compress the concentration towards the comet more), but here is in reasonable accord with expected ejection velocities for particles in a Leonid trail that would produce visual meteors.

(ii) The density becomes diluted with time, since the separation between particles increases (any particle with a longer orbital period gets progressively further behind a particle whose period is shorter). In this approximation of no gravitational perturbations, the trail necessarily lengthens at a constant rate [see equation (3)].

particles are present at n=1, 2, etc. If one considers a fixed group of particles, e.g., those with $\Delta a_0 = +0.1$, then their time lag relative to the comet is greater when n=2 than n=1, and so on.

Figure 4 schematically shows the variation in particle density along the trail. There is also a density variation *across* the trail, discussed later in Section 2.3. The density *along* the trail is the product of two terms:

$$f_a(\Delta a_0)\ f_M \qquad (4)$$

The first depends on the *initial* distribution of particles as a function of Δa_0 [cf. point (i) in Figure 4 caption]. The second term depends on the *evolution* of the trail [cf. point (ii)], McNaught & Asher (1999a) using the notation f_M for 'mean anomaly factor', since particles gradually stretch along the trail in mean anomaly, diluting the density, as the trail evolves. To a first approximation, the trail stretches linearly with time as shown by equation (3), and so $f_M = 1/n$.

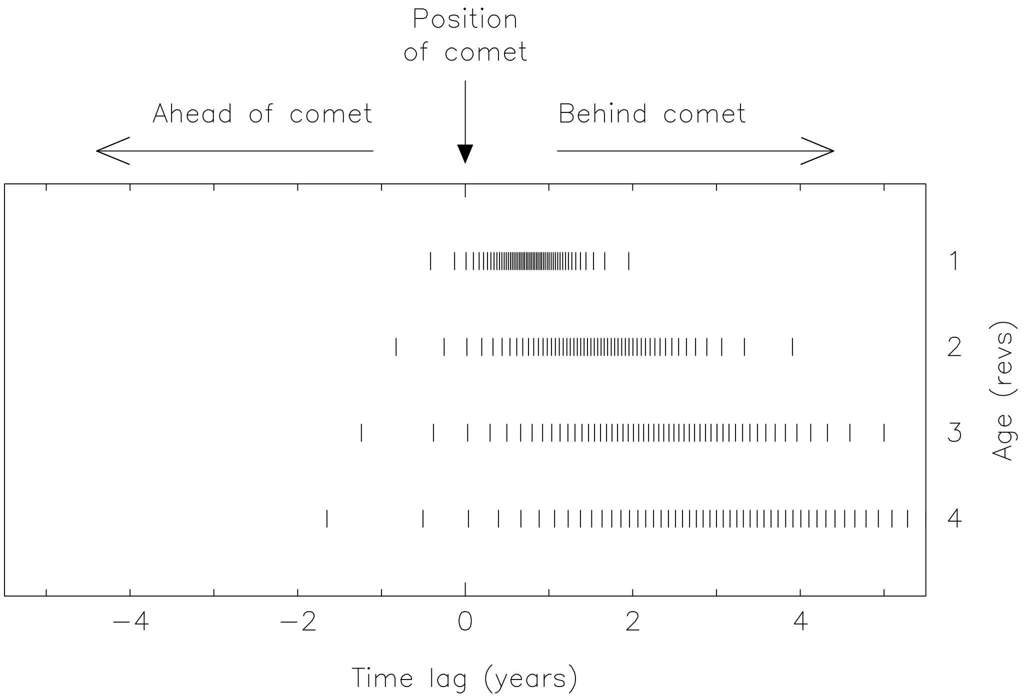

Figure 5: *Evolution of a Leonid dust trail, shown after 1, 2, 3 and 4 revolutions, neglecting gravitational perturbations, but allowing for radiation pressure at a suitable average value for particles that produce visual meteors. Cf. Figure 4.*

Considering a particle distribution as a function of Δa_0 rather than of ΔT has the advantage that $f_a(\Delta a_0)$ can be related directly to ejection models, whereas ΔT immediately after ejection is zero for all particles. Meteoroid ejection processes determine the distribution f_a and so the adopted f_a is model dependent. However, realistic ejection processes are likely to lead to a distribution that concentrates towards the cometary value a_0. In Figure 4 an idealized distribution (Gaussian) in Δa_0 was assumed (cf. Figure 2 of McNaught & Asher 1999a), with a width that would result from ejection speeds of up to a few tens of $\mathrm{m\,s^{-1}}$. These speeds are reasonable for the size of Leonid meteoroid capable of producing a typical visual meteor (Arlt & Brown 1999).

If solar radiation pressure is negligible, then f_a is expected to be centered at zero, $\Delta a_0 = 0$ corresponding to 'Position of comet' in Figure 4. However, sunlight falling on meteoroids exerts a force on them. As radiation pressure obeys an inverse square law like gravity, the effect for any given meteoroid is equivalent to reducing the Sun's gravity by a constant proportion (by a higher proportion for smaller particles). That is, the Sun is effectively pulling the meteoroid around its orbit less strongly, and so the meteoroid takes longer to complete each revolution. The effect is small but not negligible for visual meteor sized particles. Therefore imposed on the range of orbital periods above and below the cometary value (Figure 4) is an overall tendency for periods to be longer, and trails to shift backwards relative to the comet (Figure 5).

If a section of a given trail intersects the ecliptic in mid-November of a given year, the value of Δa_0 of this trail section is essentially specified by equation (3), since ΔT is the time lag from the comet reaching the ecliptic to mid-November. In a rigorous calculation, gravitational perturbations are included, rather than simply using (3). It seems easiest (cf. McNaught & Asher 1999a) to quote Δa_0 for purely gravitational solutions and to be aware that a gravitational solution at, e.g., $\Delta a_0 = +0.2$, corresponds to a solution including gravitational perturbations and radiation pressure at $\Delta a_0 = 0$. Since the peak density in reality is at $\Delta a_0 = 0$, and since in reality radiation pressure exists, the peak density (i.e., the maximum of the function f_a) when the model has been expressed in terms of purely gravitational solutions will be at some positive value of Δa_0. Thus the offset of the maximum of f_a from $\Delta a_0 = 0$ depends on radiation pressure, while we saw above that the width (in Δa_0) of the f_a distribution depends on ejection processes. Both these depend on the size and density of particles, but as a first approximation, suitable values for visual meteor sized particles (i.e., a single value for the width and a single value for the offset) can be assumed (in fact can be fitted from past storms; Section 2.3).

For the first couple of revolutions in the evolution of a trail, (3) usually holds to a very good approximation, i.e., ΔT is proportional to Δa_0 at any one time. However, as n increases, (3) becomes more affected by planetary perturbations, which continuously change a of the comet and of meteoroids. Moreover, the effect on a varies along the trail, and therefore different sections of a trail stretch by different amounts (as the amount of stretching is related to ΔT). Equation (3) is helpful for understanding how trails form, allowing a convenient expression for ΔT since Δa_0 is a constant for a particular section of a trail (Δa_0 relates to a single time, namely the ejection time, whereas Δa would be a continuously changing function), but in practice, perturbations must be calculated. Thus perturbations cause f_M to be a function of position along a trail, and the density to be uneven. This effect on f_M can, however, be evaluated precisely, i.e., whereas f_a is model dependent, f_M is not.

Although (3) becomes increasingly inaccurate, ΔT does at least remain a smoothly increasing function of Δa_0 for quite a few revolutions, except in a few short, isolated ranges of Δa_0. A trail tends to be disrupted in these short ranges, as was suggested by Stoney & Downing (1899a):

> Through one of these [segments of the ortho-Leonids] the earth passed in November 1866, and on that occasion there was withdrawn from it that small portion which consisted of meteors which either encountered or passed close to the earth. Those that actually plunged into the earth's atmosphere were destroyed: those that passed near were deflected, and were also either accelerated or retarded, and they thus became clino-Leonids.

Thus on each successive perihelion passage, small sections (spaced a year apart) of each trail are scattered into the Leonid background. Although the process requires more detailed modelling, it appears that trails are significantly scattered, to the extent that it is no longer appropriate to describe them as single, coherent entities, after a dozen revolutions or so. Therefore perturbations firstly cause density variations along trails by affecting f_M, and secondly limit the lifetimes of trails. The limited lifetime means that about a dozen Leonid trails can exist simultaneously, one for each of the last dozen perihelion passages of the comet.

2.2 Trail intersections with ecliptic

Intersection points of dust trails with the ecliptic were shown in Figures 2 and 3 for 1866 and 1899, and can be calculated for mid-November of other years. For this purpose, an idealized model is used, in which transverse ejection at perihelion is assumed, because this is sufficient to generate particles with values of a_0 differing from the cometary value. An effective difference in a_0 (i.e., an actual difference in orbital period) can equivalently be produced by radiation pressure (cf. Kondrat'eva & Reznikov 1985, Williams 1997, Asher 1999, Lyytinen 1999). The calculated intersection points are very similar whether Δa_0 is due to ejection velocity, radiation pressure, or a combination of the two.

Results are shown in Figures 6–11. In Figures 6–7 (and also in Figures 2–3 earlier), trails 1 to 6 revolutions old are plotted, and in Figures 8–11, trails 1 to 9 revolutions old are shown. Within these limits, trail cross sections are absent only if no part of the trail crosses the ecliptic in mid-November of that year. For example, in Figure 7, the section of the 1899 trail that supposedly had the correct orbital period to bring it to the ecliptic in 1998 November had its evolution disrupted because of a fairly close approach to the Earth in 1965 (cf. last paragraph of Section 2.1). For ease of comparison in seeing nodal displacements caused by perturbations, all the Figures depict the same area in absolute space, the drift in dates over a hundred years being due to precession of the equinoxes. Progressing through Figures 7–11, a pattern is evident whereby after the comet has passed, the individual dust trails separate, i.e., for larger ΔT, the ecliptic intersection points of the various trails are distributed over a wider region. In Figure 3, with ΔT being only four months, the trails were quite close to the comet node. In 3-dimensional space, the trails are wavy lines converging on the comet.

Encounters with the same trail, the one generated at the 1899 return, when it was respectively 2 and 3 revolutions old produced the 1966 and 1999 storms (Figures 6, 8). This theory of young dust trails predicts no storm in 1998 (Figure 7), and indeed the peak Leonid ZHR was well below storm level (Arlt & Brown 1999). The impressive fireball outburst was due to larger meteoroids subject to different dynamical behavior associated with a resonance, over longer time-scales than the lifetimes of a few centuries for the dust trails being described here (Asher *et al.* 1999, Arlt & Brown 1999). This material ejected a longer time ago can also be regarded as forming into trails, but these are older, 'resonant trails', as contrasted with the younger trails that produce storm level activity and that are the subject of the present article. The 'resonant zone' containing 55P/Tempel-Tuttle and the highest concentration of large, resonant meteoroids has moved on and will not return until the next apparition of the comet. More relevant for the next few years are the young dust trails whose cross sections are shown in the Figures. It is possible that more detailed modelling can determine whether the miss distances involved in the trail encounters in 2000 (Figure 9) will be small enough to produce storm level activity; however, although outbursts will occur, it may be better at present to be cautious about their intensity (see Section 2.3). In 2001 and 2002 (Figures 10, 11), there will certainly be encounters at small enough miss distances to produce storms.

2.3 Density cross section

Although planetary perturbations can be accurately evaluated, there is more inherent uncertainty in defining a meteoroid ejection model. *A priori* it is unclear whether this uncertainty would invalidate the dust trail model, for practical purposes. The proof, of whether the idealized model can genuinely predict meteor storms, lies in comparisons with past storms (McNaught 1999a): a successful theory must predict storms when they occur, must predict lack of storms when they do not occur, and must be able to predict the timings of storms that occur. The model determines the heliocentric distance and longitude of ecliptic crossing points of trails (Sections 1.2, 2.2). The distance component relates to the occurrence or

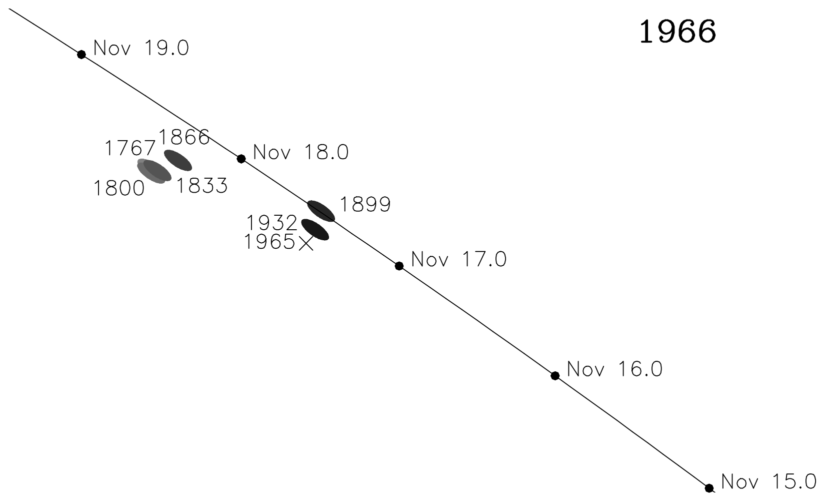

Figure 6: *Cross sections of dust trails that passed through the ecliptic in 1966 November. The comet reached its descending node, shown as a cross, in 1965 May. Cf. Figure 2 for more details.*

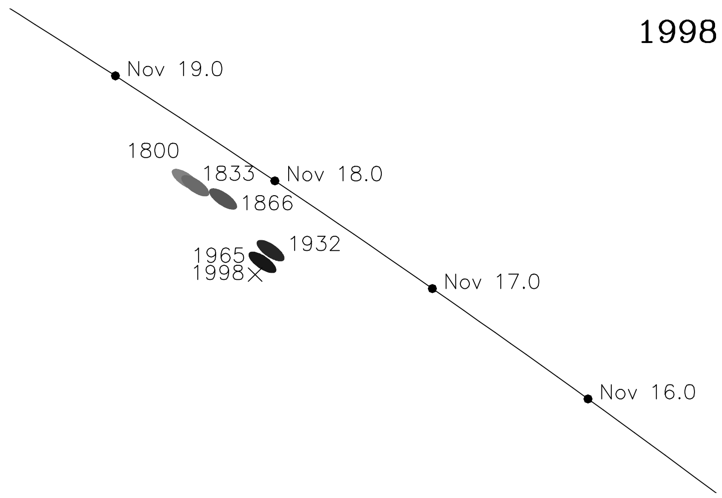

Figure 7: *Cross sections of dust trails that passed through the ecliptic in 1998 November. The comet reached the point shown in 1998 March.*

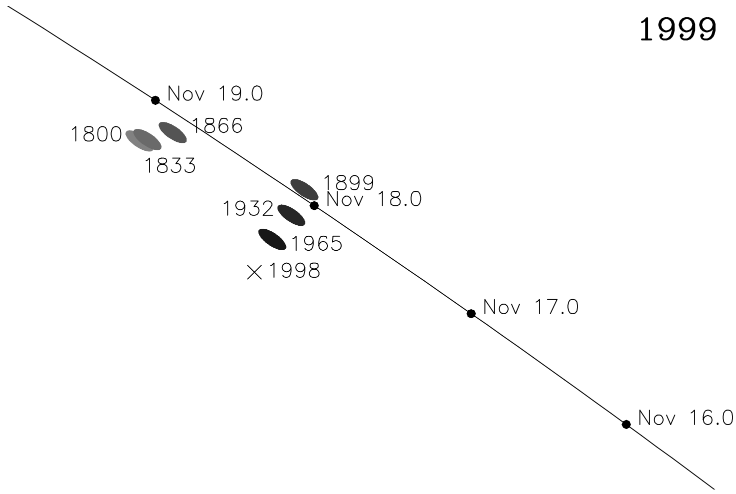

Figure 8: *Cross sections of dust trails that passed through the ecliptic in 1999 November.*

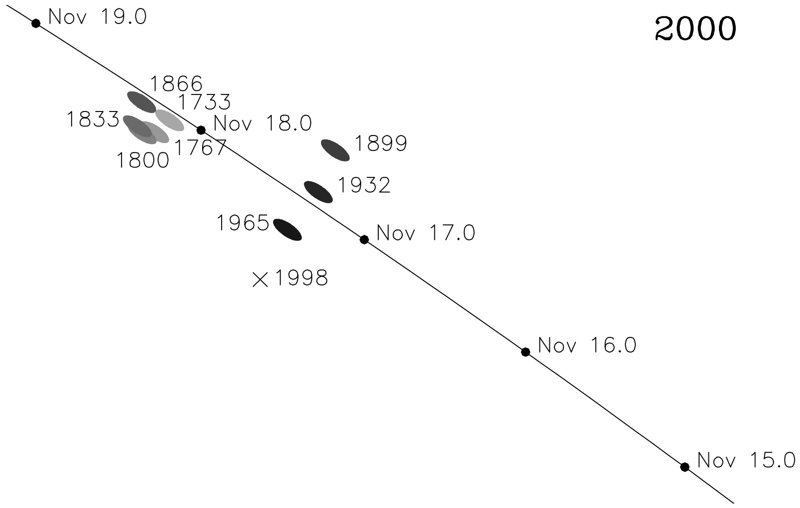

Figure 9: *Cross sections of dust trails passing through the ecliptic in 2000 November.*

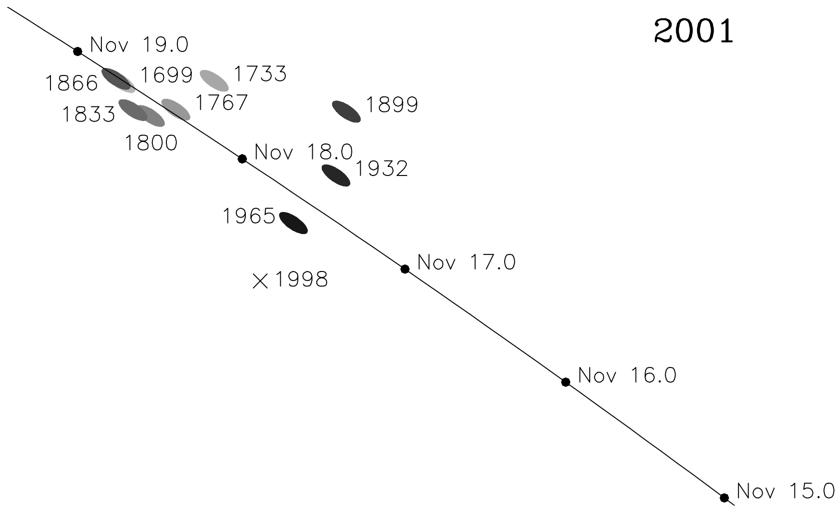

Figure 10: *Cross sections of dust trails passing through the ecliptic in 2001 November.*

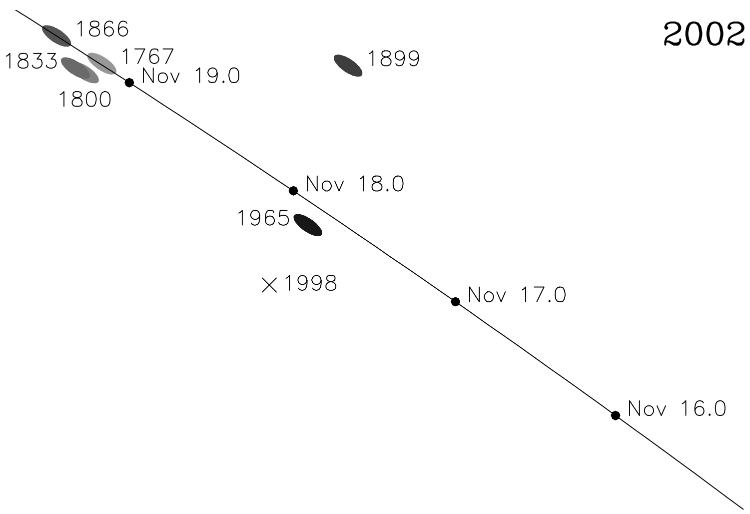

Figure 11: *Cross sections of dust trails passing through the ecliptic in 2002 November.*

non-occurrence of storms (they occur if the distance from the Earth's orbit is small) while the longitude component relates to the timing.

Accurate timings of the peaks of past storms are available (see Jenniskens 1995, Brown 1999b). Comparisons of model predictions to observed timings were done by McNaught (1999a) and McNaught & Asher (1999a, b). Including a topocentric correction, past outbursts with sharply defined peak times are fitted to an accuracy of 5 minutes. A similar accuracy applies to other streams too, e.g., the time of the observed peak of the 1998 Draconid outburst (Arlt 1998) compared to the prediction by Reznikov (1993). These accuracies of a few minutes can be compared to the hours or days that the Earth takes to traverse streams, during which outbursts can potentially occur at any time. It was therefore clear that the peak of the 1999 Leonid display would occur within a few minutes of the predicted time. In 1999 this was also within 20 minutes of the time when the Earth crossed the orbital plane of 55P/Tempel-Tuttle. The years 2000–2002 will show discrepancies of order a day compared to crossing the comet plane.

It remains to comment on how close a trail encounter has to be in order to produce a sharp outburst, the 'sufficiently close' encounters being those used in the timing comparisons with past storms. The quantity of interest is $r_{\mathrm{E}} - r_{\mathrm{D}}$, where r_{E} and r_{D} are the heliocentric distances of respectively the Earth at the encounter, and the descending node of trail particles involved in the encounter. In Figures 2, 3, 6–11, $r_{\mathrm{E}} - r_{\mathrm{D}}$ is the distance from the center of an idealized trail cross section to the Earth's orbit. The observational evidence is that meteor storms occur when the miss distance $|r_{\mathrm{E}} - r_{\mathrm{D}}|$ is less than a few Earth diameters or so. This is in accord with the size of trail cross section expected, for ejection velocities that correspond to visual meteor sized particles (cf. Section 2.1). The cross section is increased just a little by radiation pressure.

McNaught & Asher (1999a) considered whether the strength of storms, as measured by the ZHR at maximum, relates quantitatively to $r_{\mathrm{E}} - r_{\mathrm{D}}$, given that a density profile across a trail would be expected that increases sharply towards the center of the trail. The intensity of a meteor outburst would have a strong dependence on how closely the Earth encounters the center of the trail. Although numerical simulations of the ejection process could produce a rather detailed model, a more straightforward model is to assume that the peak ZHR depends only on $r_{\mathrm{E}} - r_{\mathrm{D}}$ (as well as on the along-trail parameters discussed in Section 2.1). Moreover, it is assumed that cross sections at all points along all trails are the same, subject to an overall normalizing constant accounting for the along-trail density given by (4); there are in fact theoretical reasons to expect this assumption not to be exactly true, but again the alternative would be to generate a detailed ejection model (probably a range of such models to cover uncertainties about the ejection process).

The maximum density (or peak ZHR) reached during a trail encounter (or meteor outburst) is therefore [cf. (4)]:

$$f_r(r_{\mathrm{E}} - r_{\mathrm{D}})\ f_a(\Delta a_0)\ f_M \tag{5}$$

with f_r corresponding to a density profile that increases towards the center of the trail. McNaught & Asher (1999a) took f_r as a Gaussian centered at zero. They also considered a Gaussian with the center slightly outside (i.e., further from the Sun than) the idealized r_D of the trail, as radiation pressure could move the true center very slightly outside the idealized center. Calculation of the idealized center of course includes gravitational perturbations, which for visual meteor sized particles have a much greater effect than radiation pressure on the location of the ecliptic crossing point. McNaught & Asher (1999a) fitted the offset (from

Table 1: *Leonid trail encounters in forthcoming years. Visibility maps were plotted by McNaught (1999b).*

Time of maximum (UT)	Trail	Peak ZHR	Moon age	Visible from
2000 Nov 18, $03^{\mathrm{h}}44^{\mathrm{m}}$	8-rev	100?	22	W. Africa, W. Europe, NE S. America
2000 Nov 18, $07^{\mathrm{h}}51^{\mathrm{m}}$	4-rev	100?	22	N. America, Central America, NW S. America
2001 Nov 18, $10^{\mathrm{h}}01^{\mathrm{m}}$	7-rev	2500?	3	N. & Central America
2001 Nov 18, $17^{\mathrm{h}}31^{\mathrm{m}}$	9-rev	9000	3	Australia, E. Asia
2001 Nov 18, $18^{\mathrm{h}}19^{\mathrm{m}}$	4-rev	15 000	3	W. Australia, E., SE & Central Asia
2002 Nov 19, $04^{\mathrm{h}}00^{\mathrm{m}}$	7-rev	15 000	15	W. Africa, W. Europe, N. Canada, NE S. America
2002 Nov 19, $10^{\mathrm{h}}36^{\mathrm{m}}$	4-rev	30 000	15	N. America
2006 Nov 19, $04^{\mathrm{h}}45^{\mathrm{m}}$	2-rev	100	28	W. Europe, W. Africa

$\Delta a_0 = 0$) and width of f_a, and the width of f_r, from the estimated observed peak ZHRs of the 1833, 1866, 1867, 1869 and 1966 storms and outbursts. The fitted parameters can then be applied to forthcoming trail encounters to predict the peak ZHR. The 1969 outburst is not used in the fit because it was at the comparatively large Δa_0 of $+0.9$ and it is unlikely that a single Gaussian function f_a is valid over such a wide range of Δa_0.

For reference, data relating to the next few years are listed in Table 1. The estimated ZHRs may in due course be adjusted if the work is refined. The times are unlikely to be revised, and certainly not by more than a few minutes. In 2006 there will be a similar Δa_0 to 1969, and so the peak ZHR for the 2006 encounter alone is estimated simply from comparison with 1969 alone. The ZHRs in 2000 are especially uncertain using a fit based on equation (5) because the $r_{\mathrm{E}} - r_{\mathrm{D}}$ values in the years used in the fit (1833, 1860s, 1966) all happened to be negative, whereas $r_{\mathrm{E}} - r_{\mathrm{D}}$ will be around $+0.0008$ AU in both 2000 encounters, so that the calculation is very sensitive to asymmetries in f_r. A storm or lack of storm in 1801 may be relevant to 2000 (McNaught & Asher 1999a). Meteor storms will occur in both 2001 and 2002, with 2001 being favored observationally owing to the ideal lunar phase.

In (5) there is no evolutionary term relating to the across-trail profile (corresponding to f_M for the along-trail profile): dynamical simulations show that the width of a Leonid trail at the descending node does not change with each successive revolution, for the first few centuries. This point is actually quite important with regard to why dense, narrow trails exist at all. Particles the same distance along a trail are basically co-moving around the Sun and so undergo similar perturbations. The *differential* perturbations do not apply to particles in a single, short section of a trail. A short trail section can be perturbed towards or away from the Earth's orbit but the particles are perturbed together rather than dispersing into a wider area. If trails became wider, then the Earth would run into them more often, but the ZHR would tend to be lower. Narrow trails increase the chances of storms with extremely high ZHR.

Acknowledgments

I am grateful to Vacheslav Emel'yanenko for bringing to my attention many of the papers that I have discussed here, to Ilia Roussev for translations from Russian, and to Rob McNaught for helpful comments on the material in this article.

References

Adams J.C. (1867), On the orbit of the November meteors. *Mon. Not. R. Astron. Soc.* **27,** 247–252.

Arlt R. (1998), Summary of 1998 Draconid outburst observations. *WGN* **26,** 256–259.

Arlt R., Brown P. (1999), Bulletin 14 of the International Leonid Watch: visual results and modeling of the 1998 Leonids. *WGN* **27,** 267–285.

Asher D.J. (1999), The Leonid meteor storms of 1833 and 1966. *Mon. Not. R. Astron. Soc.* **307,** 919–924.

Asher D.J., Bailey M.E., Emel'yanenko V.V. (1999), Resonant meteoroids from Comet Tempel-Tuttle in 1333: the cause of the unexpected Leonid outburst in 1998. *Mon. Not. R. Astron. Soc.* **304,** L53–L56.

Brown P. (1999a), *Evolution of Two Periodic Meteoroid Streams: The Perseids and Leonids.* Ph.D. thesis, Univ. of Western Ontario.

Brown P. (1999b), The Leonid meteor shower: historical visual observations. *Icarus* **138,** 287–308.

Davies J.G., Turski W. (1962), The formation of the Giacobinid meteor stream. *Mon. Not. R. Astron. Soc.* **123,** 459–470.

Evdokimov Yu.V., Kondrat'eva E.D. (1972), Some observations about the origin of the Leonid meteor showers (1833 and 1966). *Trudy Kazan. Gor. Astron. Obs.* **38,** 68–73. (In Russian.)

Jenniskens P. (1995), Meteor stream activity. II. Meteor outbursts. *Astron. Astrophys.* **295,** 206–235.

Kondrat'eva E.D., Reznikov E.A. (1985), Comet Tempel-Tuttle and the Leonid meteor swarm. *Sol. Syst. Res.* **19,** 96–101.

Kondrat'eva E.D., Murav'eva I.N., Reznikov E.A. (1997), On the forthcoming return of the Leonid meteoric swarm. *Sol. Syst. Res.* **31,** 489–492.

Kresák Ľ. (1993), Meteor storms. In *Meteoroids and their Parent Bodies*, eds Štohl J. & Williams I.P., Slovak Academy of Sciences, Bratislava, 147–156.

Lyytinen E. (1999), Leonid predictions for the years 1999–2007 with the satellite model of comets. *Meta Res. Bull.* **8,** 33–40.

Lyytinen E. (2000), *IMO-News*, 2000 February 9.

McNaught R.H. (1999a), On predicting the time of Leonid storms. *The Astronomer* **35,** 279–283.

McNaught R.H. (1999b), Visibility of Leonid showers in 1999–2006 and 2034. *WGN* **27,** 164–171.

McNaught R.H., Asher D.J. (1999a), Leonid dust trails and meteor storms. *WGN* **27,** 85–102. Update: *IMO-News*, 1999 November 9.

McNaught R.H., Asher D.J. (1999b), Variation of Leonid maximum times with location of observer. *Meteorit. Planet. Sci.* **34,** 975–978.

Nakano S. (1997), Minor Planet Circ. 29285.

Nakano S. (1998), Minor Planet Circ. 31070.

Oppolzer T. (1867), Determination of the orbit of Comet 1866 I (Tempel). *Astron. Nachr.* **68,** 241–250. (In German.)

Rao J. (1999), Anticipation: the 1999 Leonid meteors. *WGN* **27,** 177–194.

Reznikov E.A. (1993), The Giacobini-Zinner comet and Giacobinid meteor stream. *Trudy Kazan. Gor. Astron. Obs.* **53,** 80–101. (In Russian) Also: *IMO-News*, 1998 September 9.

Schubart J. (1965), IAU Circ. 1907.

Stoney G.J. (1899), The Leonids. Cause of the non-appearance of the shower. *Nature* **61,** 82.

Stoney G.J., Downing A.M.W. (1899a), Perturbations of the Leonids. *Proc. R. Soc. London, Ser. A* **64,** 403–409.

Stoney G.J., Downing A.M.W. (1899b), Next week's Leonid shower. *Nature* **61,** 28–29.

Stoney G.J., Downing A.M.W. (1900), The Leonids — a forecast. *Nature* **63,** 6.

Sykes M.V., Walker R.G. (1992), Cometary dust trails. I. Survey. *Icarus* **95,** 180–210.

Upton E.K.L. (1977), The Leonids were dead, they said. *Griffith Observer* **41(5),** 3–9.

Williams I.P. (1997), The Leonid meteor shower: why are there storms but no regular annual activity? *Mon. Not. R. Astron. Soc.* **292,** L37–L40.

Yeomans D.K., Yau K.K., Weissman P.R. (1996), The impending appearance of Comet Tempel-Tuttle and the Leonid meteors. *Icarus* **124,** 407–413.